

MEASURING THE REDSHIFT OF STANDARD SIRENS USING THE NEUTRON STAR DEFORMABILITY

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A recent study has shown that redshift information can be directly extracted from gravitational wave sources. This can be done by exploiting the tidal phasing contributions to the waveform during the inspiral phase of binary neutron stars coalescences. The original study investigated the viability of this idea in the context of the Einstein Telescope using a Fisher Matrix approach and in this paper, we further explore this idea using realistic simulations and Bayesian inference techniques. We find that the fractional accuracy with which the redshift can be measured is in the order of tens of percent, in agreement with Fisher Matrix predictions. Moreover, no significant bias is found. We conclude that, when tidal phasing contributions are included in the analysis, inference of the cosmological parameters from gravitational waves is possible.

Keywords: gravitational waves – standard sirens – neutron stars – equation of state – cosmology

1. Introduction

Gravitational waves (GWs) emitted by binary systems containing either neutron stars (NSs) and/or black holes (BHs) directly encode information on the distance between the source and the observer. A Hubble diagram, from which cosmological information can be inferred, can be constructed if there is a complementary redshift measurement for each source. However, GW signals from such sources do not contain clear spectral lines as observed in electromagnetic (EM) standard candles and will therefore rely on alternative methods for redshift measurement.

Messenger and Read have shown that redshift information can be directly extracted from GWs by exploitation of the tidal phasing contributions to the waveform in the inspiral phase of binary NS coalescences.¹ This additional phasing due to the tidal deformability of NSs breaks the degeneracy between NS rest-mass and its redshift, allowing both to be measured simultaneously. Moreover, they show that Einstein Telescope (ET) could measure the redshift with an accuracy of order of tens of percent, depending on the NS equation of state (EOS) that is assumed. These results were obtained through Fisher matrix calculations and should be viewed as a lower bound on the redshift accuracy when the signal-to-noise ratio (SNR) is high.

In this proceeding, we present the first realistic investigation of the viability of this method using Bayesian inference techniques. In particular, we show the sensitivity of ET to the redshift through a comprehensive simulation.

2. Simulation

We restrict our sources to be binary NSs with component rest masses distributed uniformly in the range $m \in [1, 3] M_\odot$, and with the EOS known as MS1.² The binaries are distributed uniformly in sky location, orientation, and co-moving volume with a maximum redshift of $z = 4$. We assume a concordance cosmology, *i.e.* $h = 0.7$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$. We simulate GW signals using the frequency domain TaylorF2 waveform family for non-spinning binaries.³ The point particle description of the phase in Ref. 3 is supplemented with the tidal contribution given in Ref. 4. Finally, we simulate the noise using the one-sided power spectral density (PSD) labelled ET-B.⁵

For each simulated GW event, we calculate the posterior probability density function (posterior) for z , denoted by $p(z|d, I)$, where d represents the data and I represents the information known prior to the arrival of the data. The posterior for z is calculated via marginalisation of the joint posterior over the remaining GW parameters $\vec{\theta}$, *i.e.* chirp mass, symmetric mass ratio, right ascension, declination, polarisation, inclination, and time and phase of coalescence:

$$p(z|d, I) = \int d\vec{\theta} p(z, \vec{\theta}|d, I) = [p(d|I)]^{-1} \int d\vec{\theta} p(d|z, \vec{\theta}, I) p(z, \vec{\theta}|I). \quad (1)$$

where the second equality follows from Bayes' theorem. Since we assume that the cosmology is known, the luminosity distance is fixed by the redshift.

The likelihood of the data is given by

$$p(d|z, \vec{\theta}, I) \propto \exp \left[-2\Re \int_{f_0}^{f_{\text{LSO}}} df \frac{|\tilde{d}(f) - \tilde{h}(z, \vec{\theta}; f)|^2}{S_n(f)} \right], \quad (2)$$

where $f_0 = 20$ Hz is the lower cut-off frequency, f_{LSO} is the frequency of the last stable orbit, $\tilde{d}(f)$ is the simulated data (signal plus noise) in the frequency domain, $\tilde{h}(z, \vec{\theta}; f)$ is template waveform for which we also use the TaylorF2 waveform family, and $S_n(f)$ is the PSD.

We assume that the prior distribution of the redshift is independent of all remaining GW parameters allowing us to write $p(z, \vec{\theta}|I) = p(z|I)p(\vec{\theta}|I)$. The prior on the GW parameters, $p(\vec{\theta}|I)$, is taken to be a flat distribution over the range $m_i \in [1, 3]$ for the component rest masses, isotropic distributions for the sky location and orientation the orbital plane, and flat distributions for the time and phase of coalescences over the range $0 \leq \phi_c \leq 2\pi$ and a time interval of 100 msec around the true time. The prior on the redshift, $p(z|I)$, is taken such that the sources are expected to be distributed uniformly in co-moving volume, assuming the same cosmological parameters as for the source simulation, up to a redshift of $z = 4$. To perform the integral in Eq. 1, we use the implementation of the Nested Sampling algorithm given in Ref. 6.

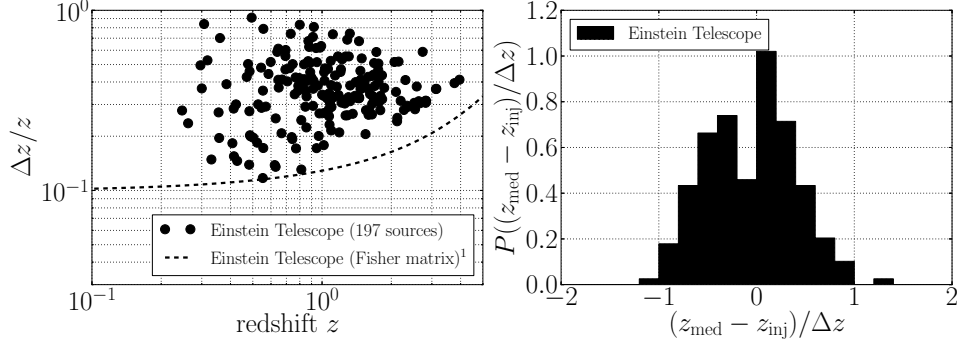


Fig. 1. Left panel: Fractional error of the redshift as a function of the true redshift for the Einstein Telescope (circles), and the corresponding sky location and orientation-averaged Fisher matrix results¹ (dashed line). The fractional error varies between 10-100 percent. Right panel: Distribution of fractional bias, $(z_{\text{med}} - z_{\text{true}})/(\Delta z)$, where z_{med} is the median redshift and z_{true} is the true redshift. No systematic bias is found.

3. Results & Discussion

The left panel of Fig. 1 shows the fractional error of the redshift, $\Delta z/z$ (where Δz denotes the 68% confidence interval), for 197 sources with a network SNR (ET comprises of three co-located detectors) greater than 8. These results are compared to the Fisher matrix calculations similar to those in Ref. 1 but with the ET-B PSD. In line with the Fisher Matrix calculations, the redshift can be found with an accuracy of $\mathcal{O}(10^{-1})$, and the accuracy decreases as the redshift increases.

The right panel of Fig. 1 shows the distribution of the fractional bias, $(z_{\text{med}} - z_{\text{true}})/(\Delta z)$, where z_{med} is the median redshift and z_{true} is the true redshift, for the same set of sources as the left panel. No systematic bias is found.

The results shown in Fig. 1 suggest that it is indeed possible to measure the redshift by supplementing the point-particle description of the phase with corrections due to the NS tidal deformability. Whether the accuracies shown in Fig. 1 are sufficient to perform competitive cosmological inference will be the subject of forthcoming publications.

References

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